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Guitar sound hole modification and its effect on tone

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Abstract This paper investigates the possibility of acoustic guitar timbre modification through the use of sound hole inserts, which change the effective size of the instrument's sound hole. The multitude of different forms in which the acoustic guitar is produced and the tonal differences between them point towards a need among musicians for variety in the timbre of their instruments. A mechanism allowing for the changing of the sound produced by an existing instrument could therefore allow for flexibility and adaptability which has thus far not been possible with acoustic chordophones. One of the factors which greatly influences the acoustic guitar's tone is the characteristic of air resonances inside the instrument's resonance chamber, which are dependent on the depth and diameter of the body's opening. In this work a set of sound hole inserts is created, which after application decrease the diameter of the guitar's sound hole. Their effect on the instrument’s timbre is investigated experimentally and the achieved results are presented and discussed. Different insert diameters are also compared to investigate the more general effect sound hole diameter has on the tonal and temporal properties of an acoustic guitar.

Keywords: acoustic guitar, sound hole, timbre analysis, guitar tone, timbre modification.

1. Introduction

The acoustic guitar was created in the 19th century in response to the musician need for a louder instrument. New trends in music meant that the guitar found a new home in smaller bands and as a solo instrumental background to singing where not only was it required to be louder but to also play in a wider frequency band. This led to the creation of x-braced steel string instruments with larger resonance chambers, stronger construction and new body shapes [1]. Throughout this process many different forms of the acoustic guitar became commonly used depending on the genre of music and expected qualities. From the Parlor and Range guitars through the Grand Concert and Auditorium styles up to Dreadnought and Jumbo instruments musicians now have a wide array of instruments to choose from [2]. Such a diversity means that many musicians use multiple instruments to meet all their needs. Figure 1 presents a comparison of selected acoustic guitar body types.

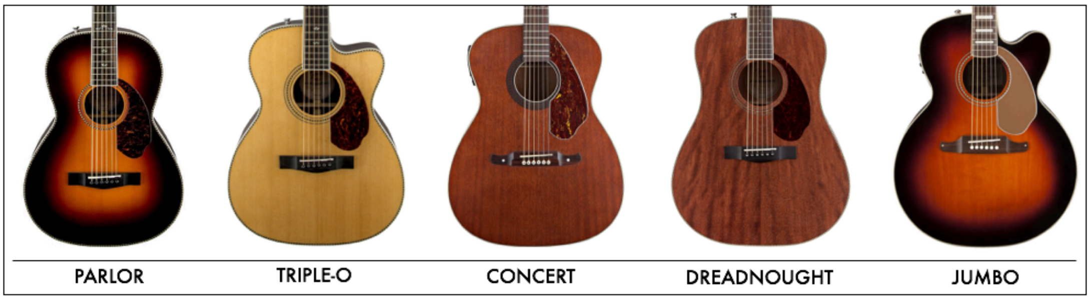

Figure 1. Comparison of selected acoustic guitar body types [3].

Unlike in the case of most electric guitars in which through the pickup selector, the tone knob or pickup coil splitting it is possible to adjust the tone of the instrument during play depending on the musical requirements the acoustic guitar has no way of adjusting its sound apart from playing technique, which can only achieve so much. For the most part a guitars timbre remains constant and is only possible to be changed through modifications such as changing the nut, bridge saddle or strings, which are all time consuming, not particularly predictable and do not offer any level of granular control [2]. It is possible for musicians, usually with the help of a luthier, to use these mechanisms to perfect an instrument, but they are not particularly effective or convenient. Another way of adjusting the tone that is used is using different plectrums [4]. This is much more convenient as pick swapping can be done even during play on stage but still offers a limited amount of control, mainly affecting the attack of the sound. The popularity of tone adjustment mechanisms in the electric guitar shows that when given such possibilities musicians find them artistically useful. It is therefore worthwhile to investigate whether it is possible to create mechanisms which allow for the adjustment of the timbre of the acoustic guitar.

There are many aspects of the acoustic guitar which can be modified with a potentially significant impact on the characteristic of the produced sound. The guitar is a complicated mechanical system which in simplification works as follows: The string is plucked, and its vibration is transmitted through the nut and saddle into the guitars neck and top plate which in turn excites the air inside the resonance chamber as well as the sides and backplate of the body [5, 6]. The frequency characteristic of the vibration is influenced by the resonance frequencies of each of these elements, but this influence is not one way with each next element influencing each other. This means that by changing the frequency response of any of these elements it could be possible to change the guitars tone to a certain extent. In this work the decision was made to investigate the modification of the sound hole as changes made to the resonance of air inside the guitars body have shown promise in the task of timbre modification in previous research [7].

The goal of this work is to investigate the possibility of modifying the sound hole of an acoustic guitar and through that achieve a perceptible change in the instrument's timbre. This will be achieved through the construction of a prototype mechanism, which will modify the instruments sound hole and conduct experiments investigating the scope of the effect on the guitars tone. At this point it is not a design requirement that the adjustment be possible to be made during play but only to investigate the range of change that is possible to be achieved through this method. It was however crucial in the design process that the use of this mechanism not require any permanent modifications to the instrument. The focus of the conducted experiment and analysis will be placed on the sound produced by the instrument and the changes in its timbre instead of other measurements such as the vibration of various elements.

2. The impact of the sound hole on timbre

The sound hole has been used by instrument designers to alter the produced sound and achieve the desired effects. This can be seen in historical acoustic guitars where f holes similar to the ones present on the violin are used or in folk guitars as for instance gypsy jazz guitars which feature oval or D-shaped sound holes. It should also be noted that today many guitar manufacturers sell instruments which deviate from the traditional central and circular sound hole design. An example of this can be seen in guitars made by Ovation where there are many smaller sound holes placed on the sides of the upper bout or ESP in their TL series where a triangular sound hole is present on the top of the upper bout. These guitars are used by professional musicians and are not considered inferior, but it is difficult to say whether these decisions were made for sound or visual aesthetic reasons.

Previous research looking at the timbre of the classical and acoustic guitar often measured the frequency response of the instrument and analysed them as resulting from the resonance frequencies of various elements of the instrument. Through such research it was noticed that there are two main mechanisms that effect this characteristic: the vibration of the air inside the resonance chamber of the instrument and the mechanical vibrations of the individual elements making up the guitar [5,6]. These processes called respectively the air and wood resonances play a crucial role in the frequency response of the guitar in low frequencies and have been linked in listener studies to strong perceptual changes in the timbre of the instrument [8]. Researchers have investigated the interdependence of the resonance characteristics of various instrument elements and their impact on each other through both experimental studies [9,10] and computer modelling [11].

The three lowest peaks in this response are caused by the first mode of vibration of the front and back plate and the resonance frequency of the guitar body working as a Helmholtz resonator [5,6]. This phenomenon also produces higher frequency harmonics, but due to them overlapping they are not as easily identified on the frequency response. It is these resonances that could potentially be shifted through the modification of the sound hole. The Helmholtz resonance describes the vibration of air inside a cavity with a single opening and its resonance frequency is dependent on the cross-sectional area of the opening, the length of the opening, the volume of the cavity and other factors which we are not able to modify in the guitar. The possibility of changing the volume of the guitar resonance chamber has been explored in a previous work [7] in which a mechanism for changing the depth of a chordophone's resonance chamber was tested and shown to sizably effect the sounds loudness, timbre and temporal qualities. That mechanism however required widespread permanent modifications to the instrument, was difficult to set, and the modifications were difficult to precisely control.

3. The created sound hole modification mechanism

A mechanism was designed in the form of inserts which allow for the modification of the sound holes diameter. After they are mounted, they don't allow for air to flow through the entire area of the sound hole, limiting its effective diameter. The prototype was created using ventilation endcaps. These are plugs used to terminate ventilation pipes made of tin, which happen to be found in the exact dimensions of the test guitars sound hole. Holes of different diameter were drilled into these plugs creating inserts which reduce the sound hole from the original 100 mm to 40 mm, 60 mm, or 80 mm. In order to make space around the sound hole for the created mechanism a part of the fretboard had to be cut off. This however could be avoided in further designs. Figure 2 shows the created inserts and Fig. 3 shows one mounted in the guitar.

Figure 2. The created inserts.

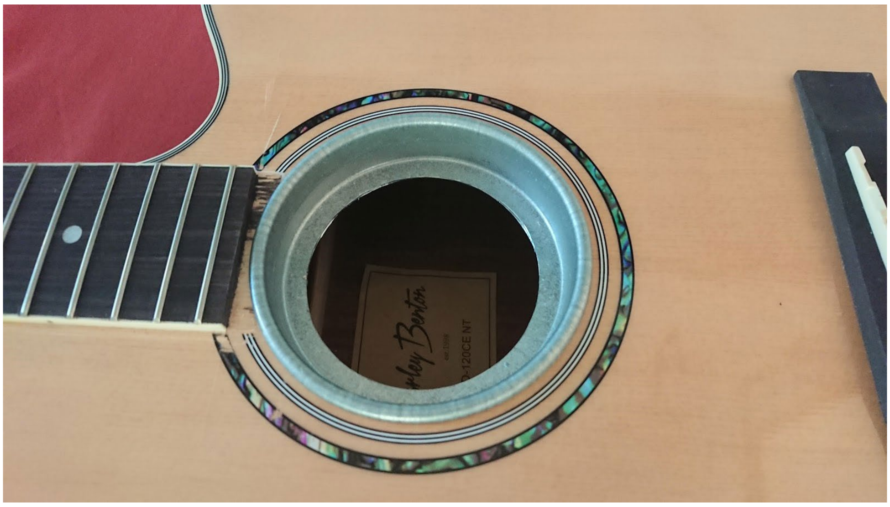

Figure 3. The 80 mm insert placed inside the guitars sound hole.

One thing that must be noted is that the use of such insert's effects not only the geometry of the guitars body but also highly changes the weight distribution on the top plate. The created elements weigh 53 g, 48 g and 39 g respectively which is a considerable amount. The addition of such a mass will therefore have a sizeable effect on the vibration of the top plate and in turn influence on the guitars tone. While this is not an issue as modifying the sound is the final goal, it must be considered when analysing the achieved results. This is particularly important when drawing more general conclusions regarding the effect of sound hole diameter on an instrument's timbre. For this use the results obtained for different inserts are more comparable.

4. The conducted experiment

To provide the greatest amount of reproducibility in the conducted experiment a special setup was created with the goal of minimising measurement variability. A guitar stand was created which allows for the repeatable mounting of the instrument in the same position while also dampening the vibration of the guitar body in as few points as possible. This also means that after placing microphones in front of the stand their position in relation to the guitar will remain constant for all measured configurations. To remove string excitation as an experimental variable a special mechanism was designed to provide a consistent pluck. This mechanism consisted of a spring from a hair clip connected to a hinge on one side and to a latch on the other with a guitar pick connected to the free end. When closed the spring is under tension and bounces away when released plucking the string. The mechanism was mounted to the guitar stand in a way which ensures its placement with regards to the guitar remains constant and the string is plucked at the same point. A similar mechanism was used in previous research and showed satisfactory repeatability [7,12]. Figure 4a shows the created mechanism.

The sound of the instrument was registered using three methods. An Audix TM1PLUS measurement microphone was placed 10 cm from the top plate below the bridge, a Shure SM 57 studio microphone was placed 15cm away from the instrument pointed at the connection between the body and neck and the inbuilt piezoelectric pickup in which the guitar was equipped. Figure 4b shows the placement of the microphones in the setup. This configuration was chosen as representative of recording techniques used to record guitars in the studio [13] while also observing the changes occurring in the instrument at different spots and with different methods. New strings were mounted on the instrument and special care was put into not touching them during the experiment to avoid wear.

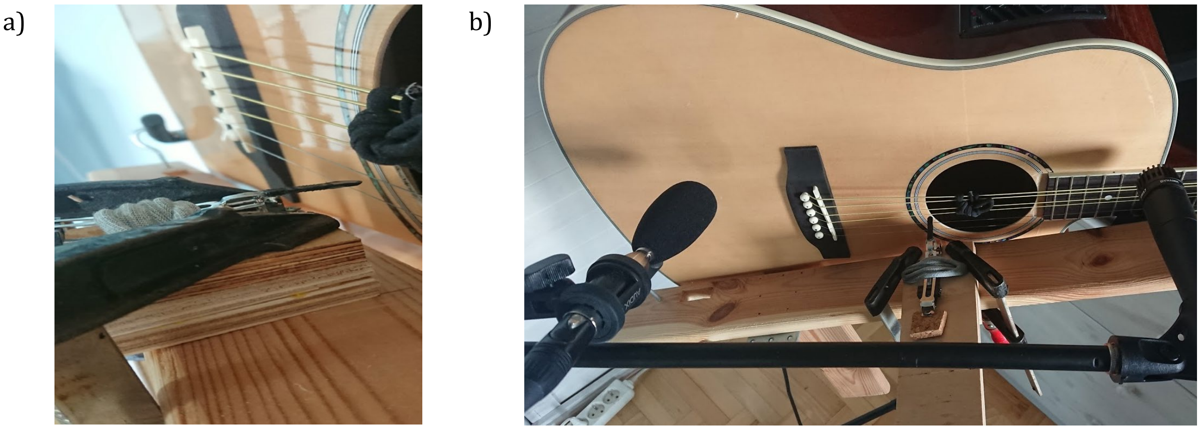

Figure 4. a) The plucking mechanism mounted to the experimental setup. b) The placement of the microphones in relation to the guitar.

To observe how the created mechanism effects the tone in a wide frequency range, measurements were conducted for 6 different notes played by the guitar: E2 (82 Hz), H2 (123 Hz), D3 (147 Hz), A3 (220 Hz), H3 (247 Hz) and F#4 (370 Hz). The used octave notation is in accordance with the MIDI standard. A series of ten plucked was recorded for each note with each of the four configurations: the original guitar and the 80 mm, 60 mm and 40 mm inserts. During recording all other strings from the plucked one were dampened using hairbands tied in multiple points.

5. Results

The created recordings were parsed, and a series of features used for audio description were extracted. The mean and standard deviation of values within a series of plucks for a given configuration was calculated. The spectrum of each recording was also calculated and averaged within series. For sake of brevity only a selected set of results can be presented within this paper, but all drawn conclusions are based on the entirety of conducted recordings. All recording methods show similar results so the results will be presented using the recordings made with the Shure SM57 microphone.

5.1. Energy parameters

One of the most important aspects distinguishing different acoustic guitar types is their loudness and as such it is important to examine the mechanisms effect on the recorded signals energy. While perceived loudness is dependent on multiple factors, most psychoacoustic models consider it to be proportional to the root-mean-squared (RMS) pressure raised to the power of between 0.6 and 0.7 [14] and as such is a worthwhile measurement to examine. Observing the obtained results, we can see that use of the inserts cause a sizable change in the RMS of the produced signal. For most pitches they cause a decrease however its extent is not equal between pitches as it is much more pronounced for lower notes then for higher ones (see Figs. 5a, 5b).

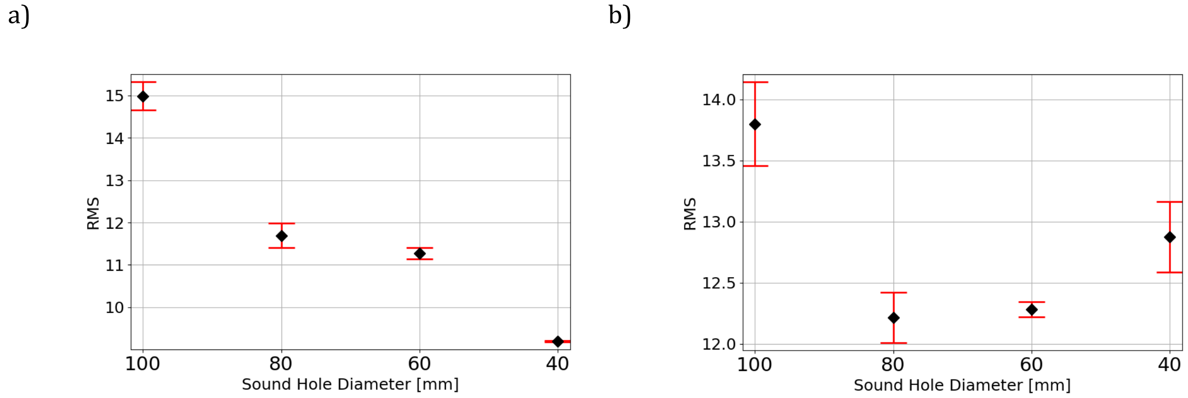

Figure 5. Comparison of RMS values with standard deviations recorded for the pitch:
a) E2 (82 Hz), b) H3 (247 Hz) with the Shure SM57 microphone, for different configurations.
Please, note that the chart values do not start at zero.

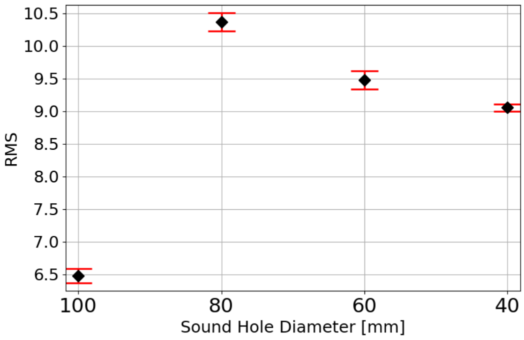

Figure 6. Comparison of RMS values with standard deviations recorded for the pitch F#4 (370 Hz)
with the Shure SM57 microphone, for different configurations.
Please, note that the chart values do not start at zero.

For the note H2 the largest measured decrease reaches nearly 50% while for H3 all are change magnitudes are below 25% of the original value. This does however change for the note F#4 for which all inserts cause an increase in the signal's RMS (see Fig. 6).

This points towards the inserts causing a large change in the frequency characteristic which is visible as a dip in the low frequencies of the instrument's characteristic while boosting higher frequencies. This can be further investigated through looking at spectral features and the spectrums of the recordings.

Another parameter worth investigating is noisiness which is defined as the ratio of the noise energy outside of the harmonic components to the total signal energy [15]. A change in its value would indicate an increase in signal noise or a decrease in the signal's harmonics which could highly influence the perception of the signal or it’s musical usability. For all insert configurations and all recording methods no strong change in this parameters value was measured. Signal entropy [16] and zero-crossing rate [15], which also describe the noise component of the signal, show larger variability between configuration but no repeatable pattern between insert use and their value change could be identified.

5.2. Spectral feature analysis

The first spectral parameter worth investigating is the spectral centroid which in multiple studies has been highly correlated with the perceived brightness of a sound [16-18] (see Fig. 7).

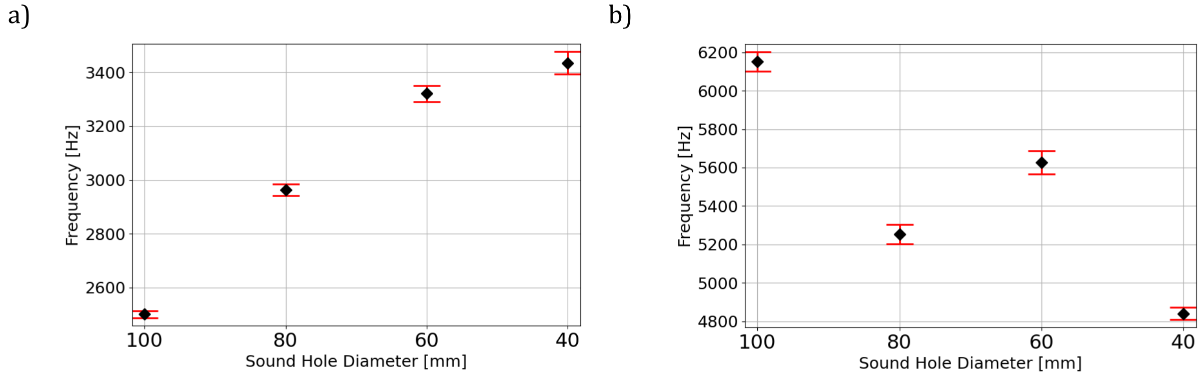

Figure 7. Comparison of spectral centroid values with standard deviations recorded for the pitch: a) D3 (147 Hz), b) F#4 (370 Hz) with the Shure SM57 microphone, for different configurations. Please, note that the chart values do not start at zero.

The graphs show that the constructed mechanism can have a substantial effect on the spectral centroid of the sound. These differences are much larger than relative differences that in psychoacoustic studies have been shown as perceptible to listeners [12, 19]. It is worth noting that for the three lower notes (see Fig. 7a) the use of inserts causes the rise of the spectral centroid which continues to be higher the smaller the insert diameter. However, for higher notes (see Fig. 7b) this relationship is reversed with the mechanism causing a drop in this parameter and the changes between diameters not having a clear direction.

Two other often used parameters are spectral rolloff, which is defined as the frequency below which 85% of the signal's energy is located and spectral spread, which describes the distribution of the spectrum around its centroid [15, 17]. Both of their values show a considerable difference between configurations and follow the same trends as described for the spectral centroid.

5.3. Harmonic feature analysis

Another category of parameters is those which focus on the energy in particular harmonic partials and the ratios between them. One such parameter is tristimulus which is defined as the ratio between particular harmonics. One of them is tristimulus 3 ($T3$) which is calculated in the following way:

$$T3(t_m) = \frac{\sum_{h=5}^{H} a_h(t_m)}{\sum_{h=1}^{H} a_h(t_m)}, \quad (1)$$

where $a_h(t_m)$ denotes the amplitude of partial h at time t_m and H is the total number of considered partials.

This feature has been shown to be very highly correlated with the perceived roughness or harshness of the sound [20]. Figure 8 shows the value of tristimulus 3 measured for the D3 note.

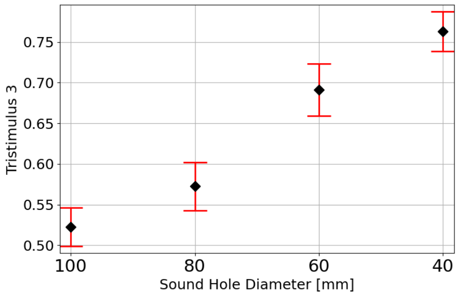

Figure 8. Comparison of Tristimulus 3 values with standard deviations recorded for the pitch D3 (147 Hz) with the Shure SM57 microphone, for different configurations.
Please, note that the chart values do not start at zero.

It's value visibly rises along with the use of the insert and along with the decrease of the sound hole diameter. This means that the energy of the higher harmonics decreases relative to the energy of the first five harmonics. The same trend is visible for all recorded pitches and seems to point towards the mechanism causing a decrease in the low frequencies of the instruments tone. This is consistent with the spectrum centroid results.

The calculated inharmonicity of the produced sound was lowered for all notes by the use of the mechanism. This may however be due to the less pronounced top end which would influence this parameter. The even-odd ratio is defined as the ratio between the energy in even and odd number harmonics of the signal and when high indicates sounds with predominant energy at odd harmonics which tend to sound sharp and shrill [16]. This parameter was increased when using the inserts for most sounds and was highly dependent on the size of the insert but depending on the played note it would either increase or decrease with the reduction of sound hole size.

5.4. Spectrum analysis

To better understand the examined phenomenon, it is worth investigating the spectrums of the recorded sounds. Figure 9 shows the average spectrums of recorded measurement series for the D3 note and Fig. 10 shows all configuration spectrums with a 10 Hz offset between them to allow for their easy comparison between the magnitudes of harmonics.

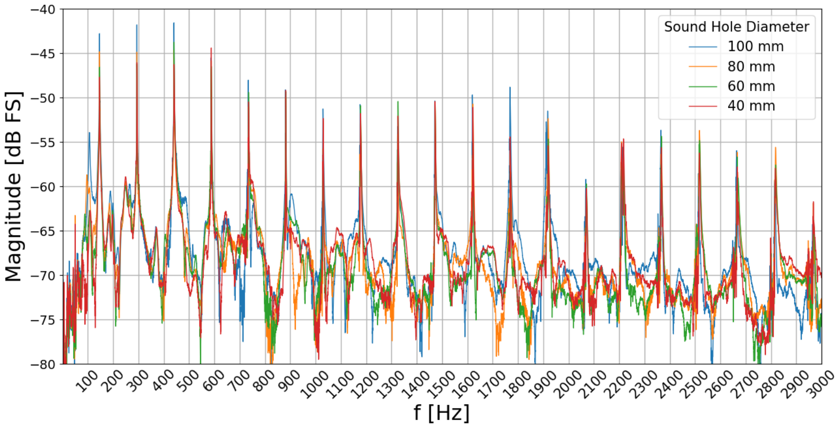

Figure 9. Comparison of average spectrums for measurement series conducted for the D3 (147 Hz) note with the Shure SM57 microphone.

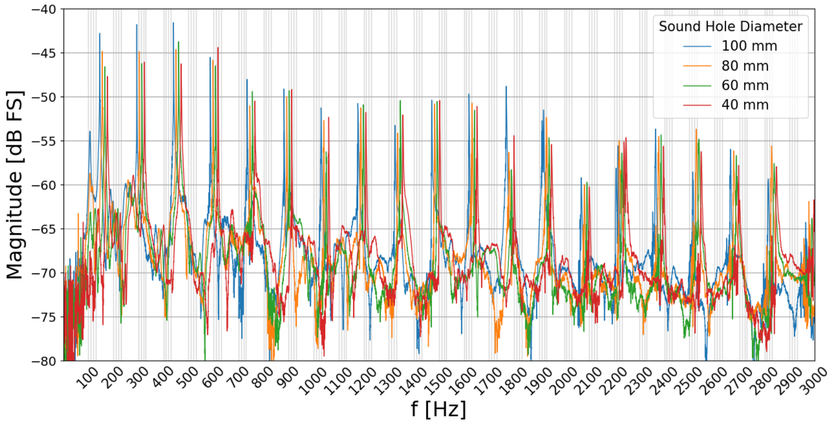

Figure 10. Comparison of average spectrums for measurement series conducted for the D3 (147 Hz) note with the Shure SM57 microphone. Please note that the spectrums have been offset by 10 Hz between each other.

What is clearly visible is that the magnitude of the first three and the fifth harmonics is decreased by between 2 and 4 dB. This is consistent with what was visible in earlier analysis through the values of the spectrum centroid and tristimulus 3 of the signals. Both showed a decrease in the low frequencies of the signal. For frequencies between 800 – 2700 Hz the harmonics are comparable apart from the twelfth harmonic at 1764 Hz which is much more pronounced without the inserts with a difference of over 5 dB. It is only in the frequencies range of over 2.5 kHz where the modified instrument becomes louder in some points. This trend also upholds the conclusions drawn from parametric analyses. Figure 11 shows a comparison of spectrums recorded for the note F#4 and Fig. 12 shows all configuration spectrums with a 10 Hz offset between them to allow for their easy comparison between the magnitudes of harmonics.

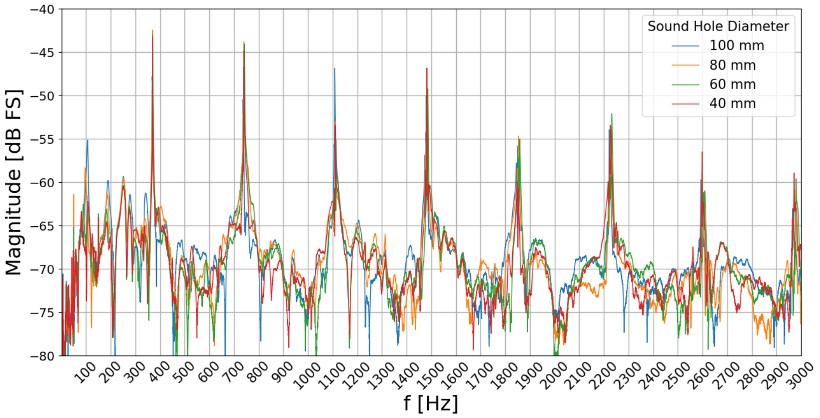

Figure 11. Comparison of average spectrums for measurement series conducted for the F#4 (370 Hz) note with the Shure SM57 microphone.

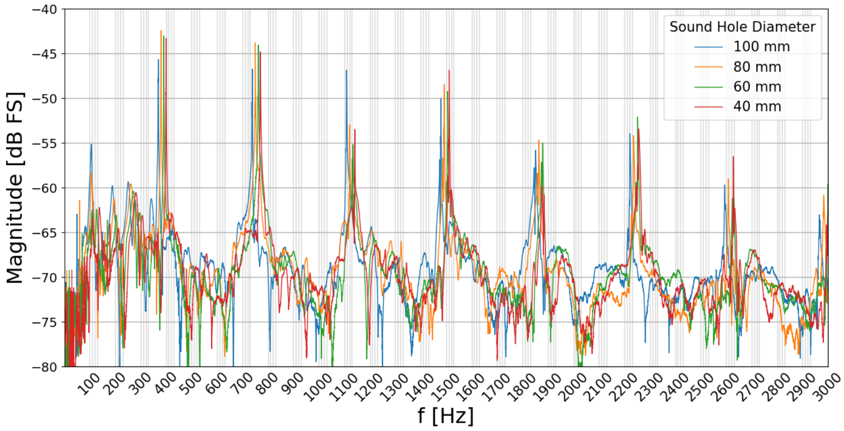

Figure 12. Comparison of average spectrums for measurement series conducted for the F#4 (370 Hz) note with the Shure SM57 microphone. Please note that the spectrums have been offset by 10 Hz between each other.

The first, second and fourth harmonic in the original guitars signal is lower than after the use of the modification mechanism. This however is reversed for the third harmonic which is dampened by over 6 dB when the inserts are used. Perceptual studies have shown that a difference of 1 dB in a single harmonic of a signal is audible [19, 21], which means that the changes visible on the presented spectrums are vastly over the threshold of perceptibility for listeners. It is also worth noting that shifting which overtones are most present in a tone can affect its character through changing the dominant intervals. This is what was shown by the previously conducted feature analysis in which all analysed parameters showed that the changes between configurations will be distinctly different to listeners.

5.5. Temporal analysis

One of the most important factors differentiating guitars is their decay time, also called sustain by musicians, which is how long they hold a note after it is plucked. It is calculated as the time it takes the amplitude envelope level to decrease by 20 dB from its maximum value [15]. For all notes and recording methods the inserts did not have a clear impact on decay time, with differences being smaller than the standard deviation of values withing a recording series. The same can be said of the temporal centroid of the signal's amplitude envelope.

6. Discussion

The results of the conducted experiment show that the constructed sound hole inserts have the capacity to affect the tone of an acoustic guitar in a degree that would be clearly audible to the listener. The guitars timbre becomes brighter and sharper with a more pronounced high end and damped low end. The energy of the signal is strongly cut for low and middle notes and boosted for high notes. At the same time the instruments sustain is not strongly affected. Crucially no anharmonic or noise components were added to the sound and the frequency of the harmonics is not changed.

While the change in the produced sound is clear it is difficult to distinguish whether this change is caused by the modification of the sound hole or due to the addition of mass to the top plate of the instrument. This can however be investigated by comparing the differences caused by the use of any insert, to that caused by the change of insert size. As the inserts are relatively similar in weight the changes between them should be predominantly due to the sound hole diameter adjustment. Investigating the presented results with this in mind brings forth certain conclusions. The very large change in signal energy seems to be strongly correlated with the additional weight as the use of inserts causes a much larger shift then differences between insert sizes. Analysis of the achieved spectrums shows that the damping achieved in the low frequencies seems correlated with insert weight much more then sound hole size. The changes between sizes become large only for frequencies over 1000 Hz. This seems to coincide with the energy results, as a lowering of amplitude in the low range would most strongly affect the signals energy. When inspecting the values of timbre features the jump due to additional weight becomes less prominent with a more even distribution between all sound hole sizes. This points towards the described effects being more related to this change in diameter. Analysing the entirety of recorded data, it seems that the addition of weight to the instruments top plate causes a decrease in the magnitude of wood vibrations especially in low frequencies, while the change of sound hole diameter causes changes in higher bands through effecting the resonances of air inside the cavity. Additionally, the base resonance frequency of the guitar body working as a Helmholtz resonator should also rise, which does explain the sizable decrease in low frequency response. These conclusions are however tentative and should be confirmed through measurements of the instrument's elements frequency response as well as in further research looking at how the addition of mass on the instruments top plate influences the instruments tonality. Such results could be used in further development as the weight could be adjusted through design and material choice to achieve the expected results

The presented results show the capacity of the described mechanism to affect a guitars tone, but the question remains whether this means of adjustment is practically usable and can potentially find use with musicians. The achieved changes are clearly musical but their nature limits possible use cases. The drop in signal energy achieved for most notes could be used in the creation of a damper. Such mechanisms are used to lower the loudness of the instrument during practice. Alternatively, the increase in brightness, sharpness and shrillness along with the energy boost for high notes could be used in the creation of a modifier, to be used during solo sections to better cut through the rest of the band. Any possible projected use case would require further development adjusting the achieved effect as well as improving useability.

7. Conclusions

This study investigated the possibility of influencing the tone of an acoustic guitar through the use of inserts which modify the effective diameter of the sound hole. A prototype of such inserts was created and experimentally tested. The results showed the capacity of such a mechanism to influence the tone of an acoustic guitar in its spectral and energy characteristics, without introducing any undesirable components into the sound. The extent of the achieved sound modifications is substantial and would be clearly audible to the average listener. The conducted tests do not allow any general conclusions regarding the effect of sound hole design on an acoustic guitar, as the created mechanism influenced many facets of the process of sound creation and the relations between them are complex beyond the scope of this work.

Additional information

The author(s) declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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